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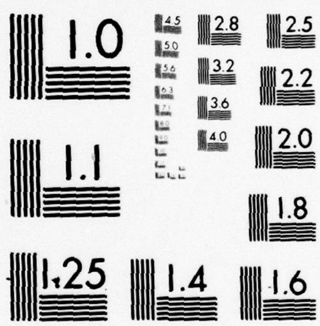

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November 1979

Distance Estimation from Cognitive Maps

Perry W. Thorndyke

A Report prepared for

OFFICE OF NAVAL RESEARCH

Rand
SANTA MONICA, CA. 90406

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R-2474-ONR Distance Estimation from Cognitive Maps. P. W. Thorndyke. November 1979.

Four experiments investigated map clutter as a source of distortion in distance estimates. In Experiments 1 and 2, subjects estimated distances between pairs of points on a memorized map. In Experiment 1, subjects learned relative distances among cities incidentally; in Experiment 2, they learned them intentionally. In both experiments, estimates increased as a linear function of the number of intervening points along the path. In Experiment 3, subjects estimated distances while viewing the map. The clutter effect was reduced but not eliminated. In Experiment 4, the clutter effect was demonstrated using subjects' pre-experimental knowledge of U.S. geography. Psychophysical power functions relating true to estimated distance provided a good fit to both memory and perception data. These results suggest an analogy between perceptual and memorial processes of distance estimation. The model providing the best fit to the data assumed that subjects perceptually scan a route from start to destination and use scan duration to determine path distance. (Author)

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PREFACE

This report documents a series of studies investigating map clutter as a source of distortion in estimates of distance. The research was performed between November 1977 and February 1979 and was supported by the office of the Director of Personnel and Training Research Programs, Psychological Sciences Division, Office of Naval Research. This research is part of an ongoing program of study on problems in the general area of spatial and locational knowledge processing.

The research reported herein was undertaken to investigate the process by which people estimate distances from learned maps and to assess potential distortions in those estimates. In the experiments described here, map clutter systematically biased people's distance estimates; thus this report should interest persons concerned with map design and with instruction in map use.

SUMMARY

The estimation of the distance between two points is frequently an important component of planning, navigation, and decisionmaking tasks. One may make such estimates using either external, hard-copy maps or an internal, cognitive map. In either case, the estimates may be influenced by a variety of characteristics in addition to the true distance.

In this study, four experiments investigated map clutter as a source of distortion in subjects' estimates of distance. In Experiments 1 and 2, subjects estimated distances between pairs of points on a memorized map. In Experiment 1, they learned relative distances among cities incidentally; in Experiment 2, they learned these distances intentionally. In both experiments, estimates increased as a linear function of the number of intervening points along the judged path. In Experiment 3, subjects estimated distances while viewing the map. With this procedure, the effect of clutter was reduced but not eliminated. In Experiment 4, the clutter effect was demonstrated using subjects' pre-experimental knowledge of U.S. geography. Psychophysical power functions relating true to estimated distance provided a good fit to both memory and perception data. These results suggest an analogy between perceptual and memorial processes of distance estimation. The estimation model providing the best fit to the data assumed that subjects perceptually scan a route (or a mental image of a route) from the starting point to the destination point and use scan duration to determine route distance.

ACKNOWLEDGMENTS

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CONTENTS

I. INTRODUCTION

The principle that a filled distance appears longer than an empty distance is one of the oldest to have received formal recognition as a perceptual law. Ptolemy invoked this principle around 150 A.D. to explain the illusion that the moon appears larger on the horizon than it does when higher in the sky. Since Ptolemy's time, a standard explanation of this illusion has assumed that the depth cues (i.e., intervening objects) between the viewer and the horizontal moon make it appear farther away than it appears to be at its zenith. However, in both cases the moon subtends the same retinal angle. Since a far object that subtends the same angle as a near object must be larger than the near object, the moon appears to be larger on the horizon.

Some of the earliest research in experimental psychology addressed this "clutter" phenomenon. Oppel (1855) showed that a row of dots appears to be longer than the same empty distance between two dots, a fact that Hering (1861) attempted to explain in his first important scientific publication. During the past 100 years, a number of studies using both children and adults have documented this illusion (Spiegel, 1937; Gaudreau, Lavoie, & Delorme, 1963; Spitz, Goettler, & Diveley, 1970; Pressey, 1974).

One historically prominent theory of perception explaining this and other visual illusions is the "eye movement" theory (Woodworth, 1938). This theory assumes that the impression of length is obtained by moving the eye along a line from the starting point to the terminus. The presence of dots along the judged path presumably causes temporary fixations or other perturbations of the perceptual scan. Therefore the distance, as reflected by the time required to perform the scan, is longer for a cluttered than for an uncluttered path.

An analog of this scanning process may occur when a person estimates distances between two geographic locations based on an internal, memorized map. For example, suppose one were estimating the distance from Boston to Washington, D.C. If the estimator knew the locations of east coast cities reasonably well but had not explicitly learned intercity distances, he or she might imagine a map of the route from Boston to Washington through New York, Newark, Philadelphia, and Baltimore. The presence of these major cities along the route would constitute clutter similar to that produced by a row of dots on a piece of paper. Thus, if the estimator scanned across a mental image of the map, the clutter along the route might increase the subjective impression of the distance. If this were the case, the cluttered route between Boston and Washington should be judged longer than the same true distance estimated along an uncluttered path (e.g., from Boston to Buffalo).

This analogy assumes a similarity between behavioral data obtained from perceptual tasks and data from memorial tasks. Such similarities have been obtained for a variety of tasks in which subjects make distance judgments about stimuli with spatial properties. Studies of perceptual scanning and distance estimation have demonstrated that perceived distance is influenced both by actual distance and by clutter. For example, Kosslyn, Pick, and Fariello (1974) found that both children's and adults' memory judgments of the distance between two objects in a room increased when barriers were interposed between the objects. Baum and Jonides (1977) and Hartley (1977) found that the time required to estimate the distance between two points increased linearly with the actual distance. Similar effects have been obtained on subjects performing these tasks using memorized information. Studies of subjects' use of visual imagery have demonstrated that the time to scan across a visual image increases linearly with scan distance and with the number of objects on the scanned path (Kosslyn, 1973, 1978; Kosslyn, Ball, & Reiser, 1978). Further, Baum and Jonides (1977) observed that the time required to compare two distances decreases with the magnitude of the difference between the distances on both perceptual and memorial tasks. Other studies have shown that estimates of distance and line length based on memory are related to true distance by psychophysical power functions similar to those obtained in perceptual experiments (Kerst & Howard, 1978; Moyer et al., 1978). Finally, numerous studies have demonstrated correspondences between perceptual and memorial performance data on other tasks that utilize spatial stimuli (Cooper, 1976; Finke & Schmidt, 1977, 1978; Kosslyn, 1973, 1975; Kosslyn & Pomerantz, 1977; Moyer, 1973; Podgorny & Shepard, 1978; Shepard, 1978; Shepard & Podgorny, 1978).

These results support the conclusion that the memory representation activated to perform these spatial tasks has much in common with the perceptual experiences of the objects themselves. In particular, it has been argued that memory representations, like percepts, can have continuously varying analog properties that accurately reflect the objects they represent (Holyoak, 1977; Kosslyn, 1973, 1975, 1978; Kosslyn & Pomerantz, 1977; Shepard, 1978; Shepard & Podgorny, 1978). Typically, such representations have been described as visual images that can be generated and manipulated in memory (Kosslyn & Pomerantz, 1977; Kosslyn & Shwartz, 1977). Such imaginal representations are spatial in the sense that they can be mapped into a coordinate system in which interpoint spatial relations preserve the topographic properties of the real objects.

Previous research has suggested that people can learn maps and retrieve information from them using visual imagery (Kosslyn et al., 1978; Thorndyke & Stasz, 1979). In the experiments of the present study, subjects estimated distances between points on memorized maps. The routes between the points contained varying numbers of intervening points. If the process of estimating distances on a memorized map is similar to that of perceptual magnitude estimation, then the presence of intervening points on the judged route should influence distance estimates. That is, increasing the amount of clutter on the judged route should increase subjects' estimates of the route distance.

This report investigates the "clutter hypothesis." Four experiments are described which establish the influence of clutter on people's judgments of map distance. Experiments 1 and 2 demonstrate this effect for estimates made from memorized, fictitious maps. In Experiment 3, the same result is obtained when subjects view the map while performing their estimates. In Experiment 4, the clutter effect is replicated for estimates based on the subjects' pre-experimental knowledge of intercity distances in the United States. Then, a variety of models are constructed of the processes by which subjects arrive at their distance estimates. These models are evaluated comparatively by fitting them to the experimental data. Finally, the relationship of these data and models to experiments in temporal interval estimation is discussed.

II. DESCRIPTION OF EXPERIMENTS

EXPERIMENT 1

Numerous studies in environmental psychology have demonstrated that environmental experiences in a given locale influence a person's perception of point-to-point distances (Golledge, Briggs, & Demko, 1969; Stea, 1969; Lee, 1970; Lowrey, 1973; Briggs, 1973; Lundberg, 1973; Cadwallader, 1976). These environmental influences include the relative attractiveness of locations as destinations, their centrality (i.e., their proximity to frequently visited areas), the familiarity of the paths connecting the locations, the direction of the paths (toward or away from central locations), and the length of time the person has resided in the locale. To isolate the effects of map clutter from these other variables, artificial map materials were used in the first three experiments of this study.

In Experiment 1, subjects initially learned a map of a fictitious road network in one of two instructional conditions. Both conditions required the subjects to learn spatial-order information about the cities on the map and the roads on which the cities were located but did not require them to learn precise locations of cities or explicit distances between them. Thus, subjects would acquire any knowledge of distances between cities incidentally. This procedure presumably approximated the manner in which people typically acquire real-world distance knowledge.

Method

Materials. A road map was constructed of a fictitious county containing 21 cities (see Fig. 1). The scale of the map was 1 inch to 50 miles. All intercity distances were multiples of 25 miles, and the minimum distance between any two cities was 25 miles. The route between any two cities could be described by the distance between them, the number of cities along the route (clutter), and the number of turns required along the route. Because the map was not designed specifically for the present experiment, not every value of clutter was represented at each route distance.

Subjects. Twenty-two UCLA undergraduates participated in the experiment to satisfy a course requirement.

Procedure. The subjects were divided randomly into two groups, the Map group and the Neighbors group, each having eleven subjects. Subjects were tested in subgroups of up to four people, but the Maps and Neighbors groups were tested separately. Subjects in the Map group were instructed to study the map so that they would be able to draw the road network and place the cities on it. Subjects in the Neighbors group were instructed to learn the relative city locations in such a way that they would be able to recall the immediate neighbors of each city along the roads to the north, east, south, and west. For example, Norwalk's neighbors were Sidney on the north, Imperial on the south, and no neighbors on the east or west. Only ordinal information about the location of the cities on the roads was required to perform this task successfully.

The subjects were then given a series of four study-test trials. On each trial, the

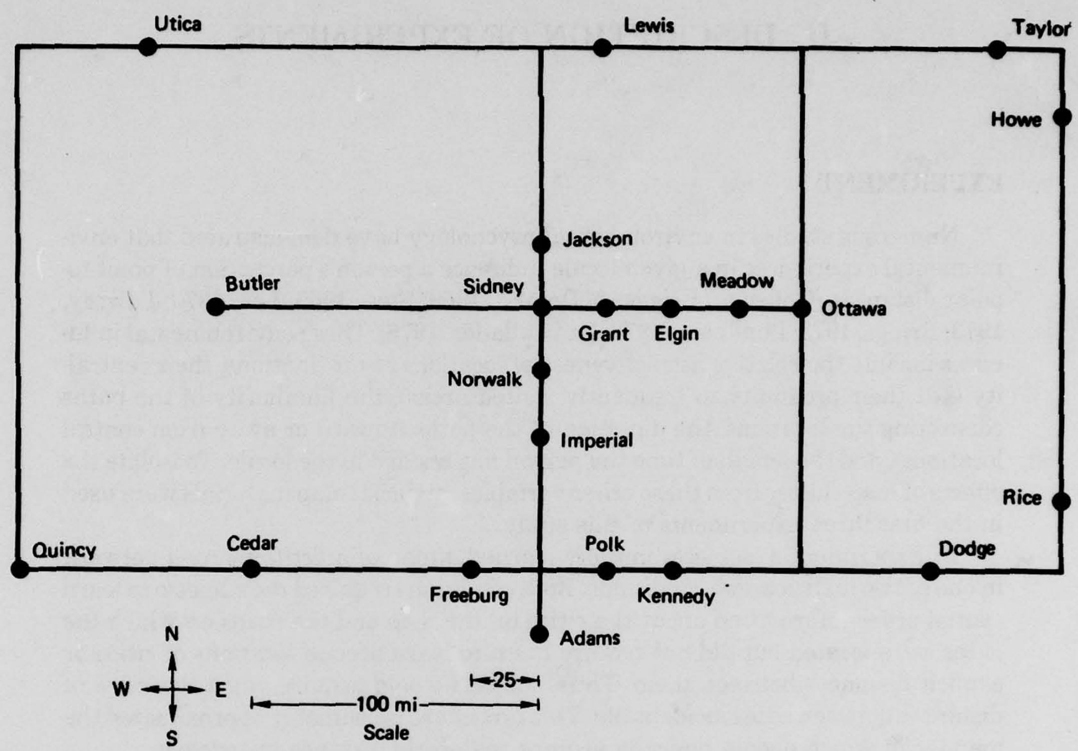

Fig. 1.—The map learned by subjects in Experiment 1

subject first studied the map, which was displayed on a screen using an overhead projector, for 2 minutes. Subjects were not explicitly instructed to attend to the scale information on the map. At the end of the 2 minutes, the map was removed and the subjects were tested on their knowledge. Subjects in the Map group attempted to draw the map. Subjects in the Neighbors group were given a sheet of paper on which the cities were listed in alphabetical order. For each city, they attempted to recall the neighbors in each direction. Unlimited time was permitted for completion of these tasks. After the fourth trial, subjects in both groups performed both the map-drawing and neighbor-recalling tasks. Then all subjects were given a sheet of paper with 58 city pairs listed on it and were instructed to estimate, for each pair, the distance along the shortest route (series of roads) connecting the pair. The true distance between cities in a pair ranged from 25 miles to 150 miles, in increments of 25 miles. The number of intervening cities between test pairs (clutter) varied from 0 to 3. The experimenter told the subjects the two explicit distances that had been displayed on the map and the distance from Freeburg to Polk (50 miles) to aid them in making their estimates.

Results and Discussic

For each subject, the mean estimated distance was computed for all pairs with a given distance and a given amount of clutter. Since pairs that were 25 miles apart did not vary in clutter, they were eliminated from further analysis. An initial analysis of variance that treated subject group, distance, and clutter as factors indicated no differences between the two instructional groups, $F(1,20) < 1$. Therefore, the data from the two groups were combined for subsequent analysis. These data are presented in Fig. 2. Each line represents the mean estimates, in miles, between the city pairs separated by the actual distance shown. To equalize the number of observations contributing to each point, the data for clutter values 2 and 3 were combined.

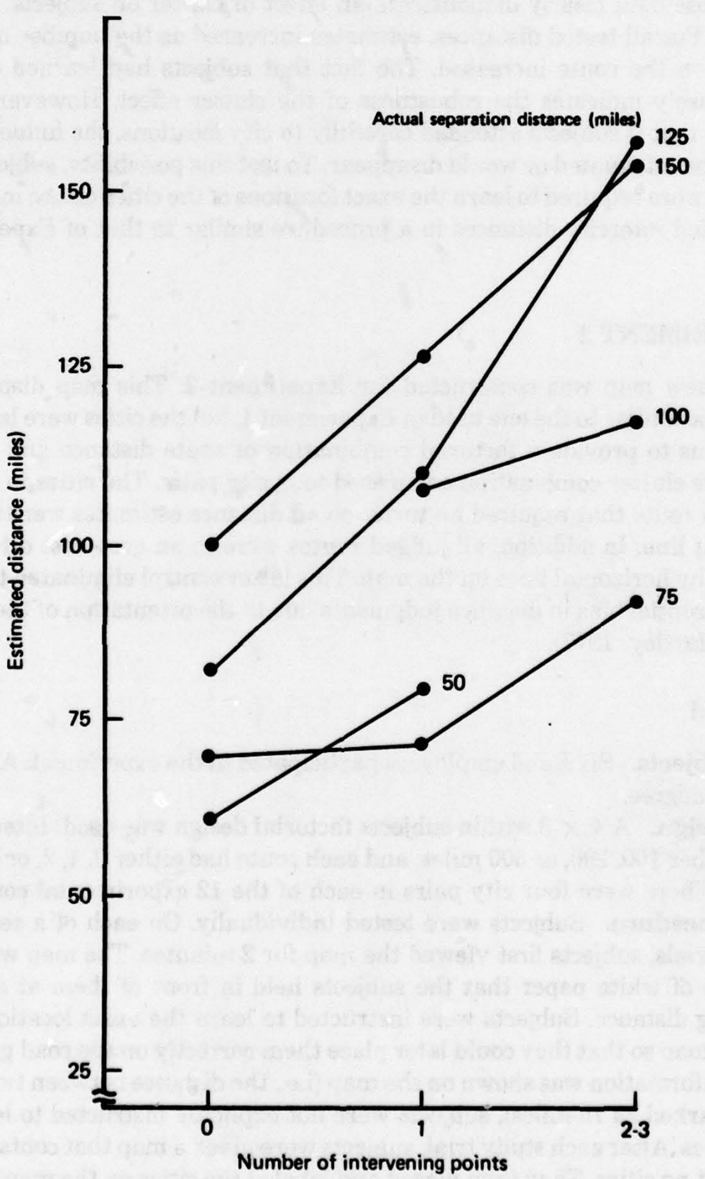

Fig. 2—Mean estimates of route distances from memory in Experiment 1

For each true intercity distance, subjects' mean distance estimates increased as the number of intervening points on the connecting route increased. An analysis of variance performed on the data for the 75-, 125-, and 150-mile pairs revealed reliable differences due to distance, $F(2,42) = 28.06$, $p < .001$, and clutter, $F(2,42) = 36.18$, $p < .001$. Post-hoc t-tests (Winer 1962) showed the differences among each pair of adjacent points, except for the first two points on the 75-mile line, to be reliable ($p < .01$). Estimates for the 50-mile pairs increased reliably with clutter, $t(21) = 2.40$, $p < .02$, while the difference in estimates for the 100-mile pairs was marginally reliable, $t(21) = 1.39$, $p < .10$ (one-tailed tests).

These data clearly demonstrate an effect of clutter on subjects' distance estimates. For all tested distances, estimates increased as the number of intervening points on the route increased. The fact that subjects had learned city locations imprecisely indicates the robustness of the clutter effect. However, it might be argued that if subjects attended carefully to city locations, the influence of clutter would be attenuated or would disappear. To test this possibility, subjects in Experiment 2 were required to learn the exact locations of the cities on the map. They then estimated intercity distances in a procedure similar to that of Experiment 1.

EXPERIMENT 2

A new map was constructed for Experiment 2. This map displayed a road network similar to the one used in Experiment 1, but the cities were laid out in such a way as to provide a factorial combination of route distance and clutter. Each distance-clutter combination comprised four city pairs. The cities in each pair lay along a route that required no turns, so all distance estimates were made along a straight line. In addition, all judged routes were in an east-west direction, represented by horizontal lines on the map. This latter control eliminated the possibility of differential bias in distance judgments due to the orientation of the route on the map (Hartley, 1977).

Method

Subjects. Six Rand employees participated in the experiment. All had at least a B.A. degree.

Design. A 4 $\times$ 3 within-subjects factorial design was used. Intercity distance was either 100, 200, or 300 miles, and each route had either 0, 1, 2, or 3 intervening cities. There were four city pairs in each of the 12 experimental conditions.

Procedure. Subjects were tested individually. On each of a series of study-recall trials, subjects first viewed the map for 2 minutes. The map was printed on a piece of white paper that the subjects held in front of them at a comfortable viewing distance. Subjects were instructed to learn the exact location of all cities on the map so that they could later place them correctly on the road grid. Although scale information was shown on the map (i.e., the distance between two of the cities was marked as 75 miles), subjects were not explicitly instructed to learn intercity distances. After each study trial, subjects were given a map that contained the road grid but no cities. They then placed and labeled the cities on the map as accurately as they could. The experimenter evaluated the reconstructed map and provided feedback on errors the subjects had made. The study-recall procedure was repeated until the subjects had accurately reconstructed the map on two consecutive trials.

Subjects were then asked to estimate distances for the 48 city pairs. The experimenter instructed each subject to imagine the route between the cities of a test pair and estimate its length, using the standard 75-mile modulus shown on the map. The city pairs were presented verbally, and each subject received a different random order of the test items.

Results and Discussion

For each subject, the mean distance estimate was computed for each of the 12 experimental conditions. Figure 3 shows the mean estimated distances across subjects for intercity routes of 100, 200, and 300 miles. On all routes, the estimated distance increased with increasing numbers of intervening points, $F(3,60) = 2.91$, $p < .05$. In addition, the differences in estimates due to distance was reliable, $F(2,60) = 58.24$, $p < .001$. The effects of clutter were the same regardless of the distance to be estimated: The interaction between the distance and clutter variables was not significant ($F = .40$).

Tests for a linear trend due to the clutter variable indicated that the linear component accounted for 97 percent of the variance. This linear trend was significant, $F(1,60) = 8.52$, $p < .01$. The best-fitting linear function was calculated for each distance function by the method of least squares. The lines representing these functions are shown in Fig. 3. The dotted lines surrounding each function indicate the 95 percent confidence interval for the regression line.

The perceived distance of an interval again increased linearly with the number of intervening points. These effects of clutter on distance estimates replicate the well-known results of perceptual studies of the filled-space illusion (Gaudreau, Lavoie, & Delorme, 1963; Spitz, Goettler, & Diveley, 1970; Pressey, 1974). In addition, Spiegel (1937) found that the size of the illusion increased with the amount of clutter in the judged area. These results are also consistent with the reaction-time data on scanning memorized maps of Kosslyn et al. (1978), who found that reaction time to scan across a route increased linearly with the number of intervening objects, and that this clutter effect was independent of the scanned distance.

The similarity between the present results and those obtained from perceptual and image-scanning experiments suggests that the experimental subjects encoded a visual image of the map and used that image to estimate distances. And indeed, all subjects reported using an image of the map to perform the estimation task. Since these images presumably preserved the metric distance information of the original map, subjects could estimate distances in the same way they would if they actually viewed the map during the task. To estimate a distance between two cities from memory, subjects presumably mentally located that portion of the map representation that contained the two cities. They then "scanned" the route between the two cities, using the standard 75-mile length as a modulus against which to compare the distance.

In Experiment 2, subjects did not perform the distance estimation task until they had precisely learned the locations of the cities on the map. Since these locations were accurate when originally learned, it is reasonable to assume that the memory distortions due to clutter were not introduced in the storage process. Rather, the distortions appear to have been produced at retrieval time, when

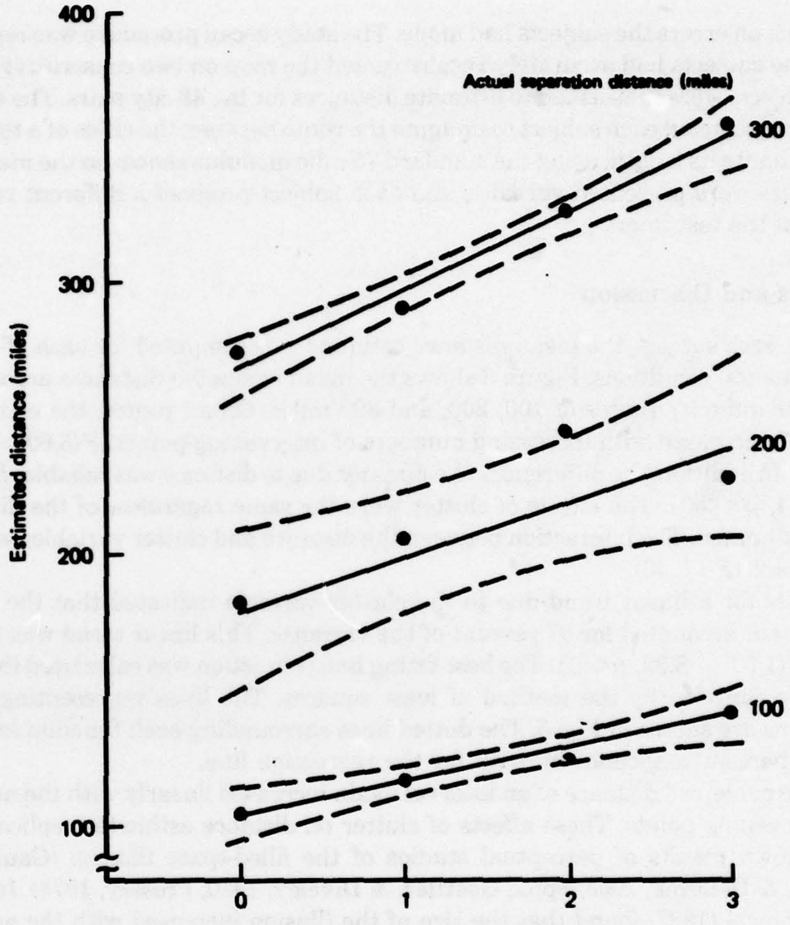

Fig. 3—Mean estimates of route distances from memory in Experiment 2

subjects performed their distance judgments. If this is the case, then subjects should show the same distortions of judgment even when using a completely veridical representation of the map. Furthermore, if subjects use a quasi-pictorial image of the map to produce their estimates from memory, the same distortions should be obtained when the task is purely perceptual. Earlier psychophysical studies of magnitude estimation obtained this same result, using simple line segments as stimuli.

EXPERIMENT 3

In Experiment 3, we attempted to replicate the results of Experiment 2 on a perceptual task, using the same materials and experimental context.

Another purpose of Experiment 3 was to compare the psychophysical functions relating route length and judged length obtained on the memory and perception tasks. Numerous psychophysical studies of line length and distance estimation have demonstrated that the relation between psychological magnitude (L′) and physical magnitude (L) can be described by a power function of the form

$$L' = kL^n , \qquad (1)$$

where n is a parameter that depends on the judgment continuum and k is a scale factor that depends on the unit of measurement (Stevens, 1975). In studies of distance estimation, the exponent n of this power function has typically been found to be close to 1.0 (Gibson & Bergman, 1954; Gibson, Bergman, & Purdy, 1955), although it can vary from .8 to 1.2, depending on the viewing angle of the target destination, the environment in which the estimates are made, and other variables (Kunnapas, 1960; Teghtsoonian & Teghtsoonian, 1969; Galanter & Galanter, 1973). However, in studies of perceived line length, the exponent of the power function is typically very close to 1.0 and is less variable (Baird, 1970; Stevens, 1975; Kerst & Howard, 1978).

When subjects use memory rather than a physical stimulus to estimate lengths, this same power function adequately describes the relationship between true length and judged length (Kerst & Howard, 1978; Moyer et al., 1978). That is, subjects seem to make an "internal psychophysical judgment" on their memory representation when asked to estimate lengths of remembered stimuli (Moyer, 1973). In Experiment 2, subjects were required to learn the exact location of the cities before they performed the distance-estimation task. If subjects' memory representations of the map preserved the spatial properties of the real map, and if the processes used to estimate distances perceptually and in memory are identical, then the exponents for the psychophysical functions in Experiments 2 and 3 should be identical.

Method

Materials. The map used in Experiment 2 was modified slightly for Experiment 3. Several roads and cities were added in such a way that city pairs 400 miles apart were shown. The routes connecting these cities contained either 0, 1, 2, or 3 intervening cities. The roads, cities, and routes used as test items in Experiment 2 were unaffected by this modification.

Subjects. Eight UCLA undergraduates participated in the experiment for course credit.

Procedure. All subjects were tested together in a single session. They were told that the experiment investigated speed and accuracy of map reading. Each subject was given a copy of the map and a sheet of paper containing a list of the 64 city pairs to be estimated. The items comprised 16 conditions: 4 true distances (100, 200, 300, 400 miles) $\times$ 4 values of clutter (0, 1, 2, 3). The city pairs were randomized, with the constraint that no two items from the same condition appeared consecutively. Subjects were told that for each item, they should find the pair of cities on the map and then estimate and write down the distance between them, using the 75-mile distance shown between two of the cities as a standard. Subjects were not allowed to use any mechanical aids to perform the estimates.

After subjects completed the task, they completed a questionnaire about the strategies they used to generate their estimates.

Results and Discussion

The data were analyzed as in Experiment 2. Figure 4 shows the mean estimates for the city pairs as a function of both true distance and number of intervening cities. Both true distance ($F(3,21) = 370.32$, $p < .001$) and clutter ($F(3,21) = 4.68$, $p < .02$) were signficant factors influencing subjects' distance estimates. There was no interaction between the two variables ($F = .98$). Newman-Keuls tests revealed

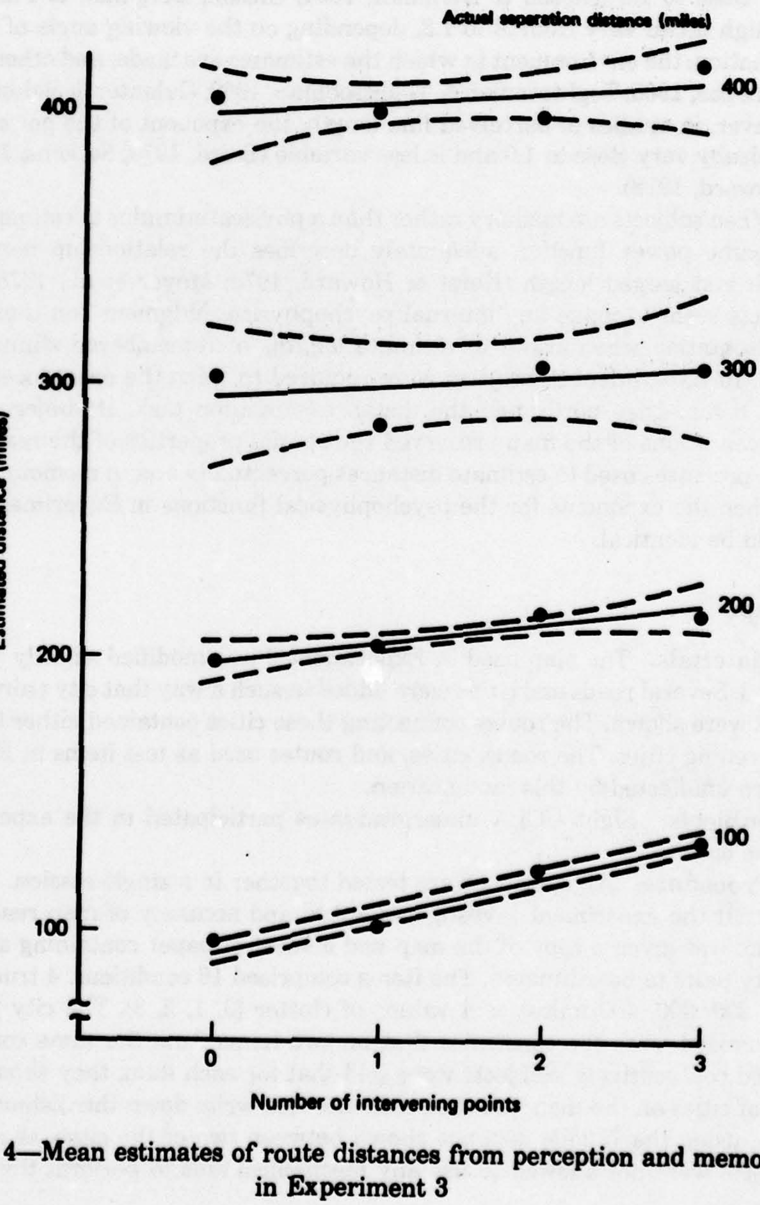

Fig. 4—Mean estimates of route distances from perception and memory in Experiment 3

that the mean estimated distance with three intervening cities was reliably larger than that with two intervening cities, and that the mean with two intervening cities was larger than that with one intervening city ($p < .01$ for both). Furthermore, the linear component of the variation due to clutter was significant, $F(1,84) = 11.26$, $p < .01$, and this component accounted for 80 percent of the variance due to the clutter variable. Figure 4 shows the best-fitting regression lines for subjects' estimates and the 95 percent confidence intervals for these regression lines. Comparison of Fig. 4 with Fig. 3 reveals that, in general, subjects estimating distances perceptually showed less variation than subjects performing estimates from memory.

The psychophysical power functions relating true to estimated distance were computed for the data from Experiments 2 and 3. First, the geometric means of the magnitude estimates for city pairs in each condition were computed. Then separate power functions were fit to the group means for each value of clutter by the method of least squares. These data are displayed in Fig. 5, using log-log coordinates. When the data are plotted in this manner, the slope of the line connecting each set of points provides the exponent for the psychophysical power function. For both memory data and perception data, power functions provided a good fit to the data

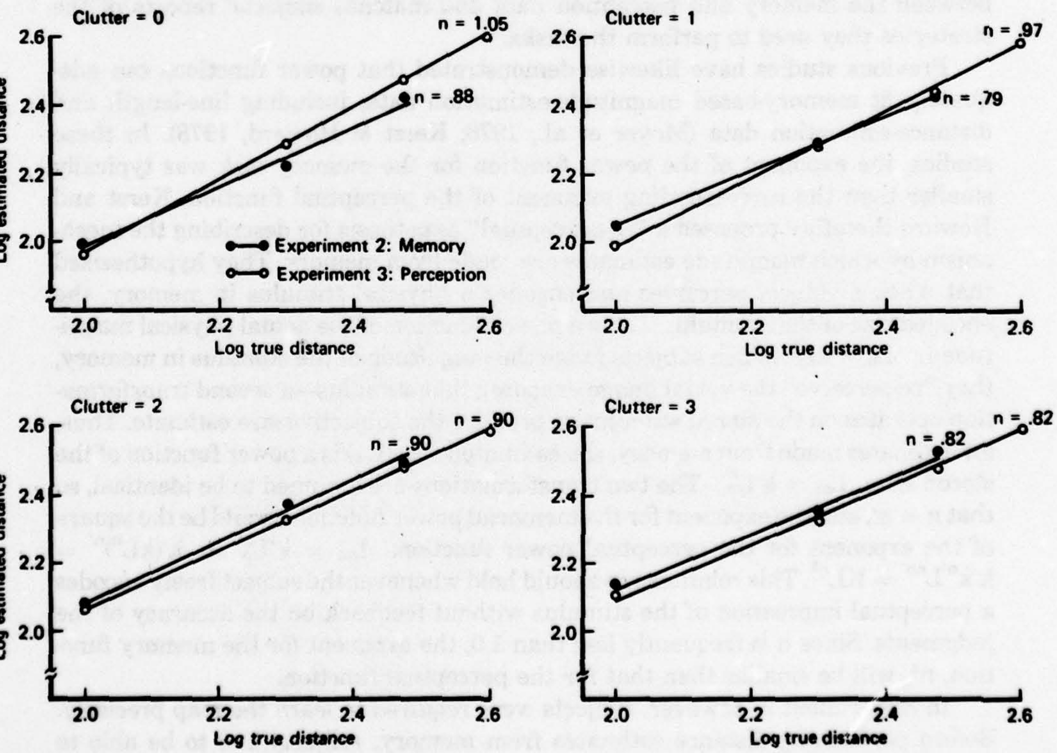

Fig. 5—Log geometric mean estimates of route distances as a function of the true distance for each value of clutter in Experiment 3

(r = .99 or 1.0 for all eight sets of data). Furthermore, for city pairs with two or three intervening cities, the exponents for the memory and perception experiments were identical. For the other two values of clutter, the exponents for the perception condition were slightly larger than those for the memory condition. All exponents were within the range of values observed in earlier studies of magnitude estimation of length (Baird, 1970).

When subjects estimated distances between cities while viewing the map, the presence of intervening cities on the route increased the estimated distance. This result replicates, in a novel context, the finding from earlier studies that filled spaces are perceived to be larger than unfilled spaces. This clutter effect was also obtained when subjects estimated distances in memory. Although the magnitude of the clutter effects differed between the memory and perception tasks, the qualitative correspondence between these distortion effects suggests that the estimation processes in perception and memory and the representation on which the processes operate are similar in the two conditions. Further, with the clutter effects removed from consideration, the close fit of psychophysical power functions to both the memory and perception data also indicates the similarity between these estimation processes. In particular, subjects seem to encode the map in memory in an image that preserves the spatial relations of the real map. When asked to estimate distances between cities, subjects scan a visual image of the map in the same way that they scan the real map. Thus, decision processes in both perception and memory conditions appear to be perceptual in nature. This both explains the isomorphism between the memory and perception data and matches subjects' reports of the strategies they used to perform the tasks.

Previous studies have likewise demonstrated that power functions can adequately fit memory-based magnitude-estimation data, including line-length and distance-estimation data (Moyer et al., 1978; Kerst & Howard, 1978). In these studies, the exponent of the power function for the memory task was typically smaller than the corresponding exponent of the perceptual function. Kerst and Howard therefore proposed a "re-perceptual" hypothesis for describing the mechanism by which magnitude estimates are made from memory. They hypothesized that when a subject perceives and encodes a physical stimulus in memory, the encoded size of that stimulus (L_p) is a power function of the actual physical magnitude L: $L_p = kL^n$. When subjects judge the magnitude of the stimulus in memory, they "re-perceive" the visual image encoding that stimulus—a second transformation operates on the stored stimulus to produce the subjective size estimate. Thus, for estimates made from memory, the estimated size (L_m) is a power function of the stored size: $L_m = k'L_p^{n'}$. The two transformations are assumed to be identical, so that $n = n'$, and the exponent for the memorial power function should be the square of the exponent for the perceptual power function: $L_m = k'L_p^{n'} = k'(kL^n)^{n'} = k'k^{n'}L^{nn'} = KL^{n^2}$. This relationship should hold whenever the subject freely encodes a perceptual impression of the stimulus without feedback on the accuracy of the judgments. Since n is frequently less than 1.0, the exponent for the memory function, n^2, will be smaller than that for the perceptual function.

In Experiment 2, however, subjects were required to learn the map *precisely*. Before performing distance estimates from memory, subjects had to be able to reproduce the exact location of all cities on the map. Unlike Kerst and Howard's subjects, the subjects in Experiment 2 presumably possessed a veridical representation of the map in memory. Thus, the image on which the memorial estimates were based should have been identical to the physical map. If this were the case, then the exponent from the power function obtained in the memory and perception conditions should have been identical. This was, in fact, the case for two of the four values of clutter used in Experiment 2.

Experiments 1 through 3 demonstrated the effect of clutter on distance estimates with artificial laboratory materials. While the clutter effect occurred even when subjects were viewing the map, the obtained differences among clutter conditions were not large. These results leave open the question of whether the clutter effect can be demonstrated using pre-experimental geographic knowledge and in the presence of other variables. Experiment 4 investigated whether or not the illusion could be replicated using subjects' prior knowledge of U.S. geography.

EXPERIMENT 4

Method

Subjects. Eighteen subjects participated in the experiment. Some were volunteers from the Rand staff, and some were UCLA undergraduates who participated for course credit. All subjects were at least of college age.

Materials. Two maps of the United States were used in the experiment. One map displayed only the national borders; the other displayed state outlines as well. Both maps displayed the names and locations of the 45 most populous cities in the United States. These cities all had a population of at least 300,000 in the 1970 census.

From this set, 64 city pairs were constructed. The city pairs were selected according to airline distance between the cities and the number of cities lying along the route connecting them. The intercity distances were either 400, 700, 1000, or 1400 miles. While few actual distances were exactly one of these values, no distance deviated by more than 10 percent from one of them. There could be either 0, 1, 2, or 3 intervening cities along a route. A city was defined to be "on the route" between two other cities if it was within 50 miles of the direct path connecting the two cities. These two variables were combined factorially so that there were four city pairs in each of the 16 conditions. The mean route distance for the four city pairs in a given condition (e.g., distance = 400, clutter = 0) did not deviate by more than 10 miles from the mean for any other city pair with the same sepatation distance but in a different clutter condition (e.g., distance = 400, clutter = 1).

Design. A 2 × 4 × 4 within-subject design was used. Subjects performed distance estimates in two task conditions: from memory and while viewing the map. Each route to be estimated was either 400, 700, 1000, or 1400 miles in length and contained 0, 1, 2, or 3 intervening cities.

Procedure. Subjects were tested in groups. They worked through booklets containing the maps and problems, the first page of which showed an outline map of the United States with state boundaries and, below the map, a numbered alphabetical list of the 45 cities. Subjects were informed that the experiment investigated knowledge of U.S. geography. They were instructed to place each city on the map with a pencil and label it with its number. Following the number, they were to write a number between 1 and 10 indicating their familiarity with the city. If they knew the exact location of the city and had visited it many times, they would write 10; if they had great uncertainty about the location of the city, had never visited it, and knew nothing about it, they would write 1.

Subjects then spent 2 minutes studying the map showing the state outlines and city locations to familiarize themselves with cities about which they had been uncertain. Following this brief study period, the map was removed and subjects worked through the list of city pairs. They were instructed to estimate the airline distance between the cities of each pair by imagining them on a map of the United States. They were given three distances to use as standards: San Francisco-Los Angeles = 350 miles; San Francisco-New York = 2,571 miles; and Miami-Seattle = 2,734 miles. A single random order of items was used for all subjects.

The sheet on which the estimates were written was then removed, and subjects were given a map showing the cities but not the state borders. They repeated the estimation task, with the same set of items, while viewing the map and the cities. Subjects' previous estimates were not available to them during this task.

Results and Discussion

Subjects' placements of cities on the map were scored to determine the accuracy of their knowledge of locations. Three subjects were replaced because of inadequate knowledge. The other subjects all placed the cities correctly to within 50 miles of their true locations.

The distance estimates were analyzed separately for the memory and perception tasks. The resulting data are shown in Fig. 6. The straight lines were fit to the data using the method of least squares.

For both memory and perception tasks, mean estimates increased as the distance between cities increased ($F(3,272) = 118.78$, $p < .01$ for memory; $F(3,272) = 840.69$, $p < .01$ for perception). Distance estimates also increased with increasing numbers of intervening cities for both tasks ($F(3,272) = 3.34$, $p <$ for memory; $F(3,272) = 10.01$, $p < .01$ for perception). The interaction between these two variables was not significant in either analysis. For both the perception and memory data, Newman-Keuls tests showed the overall mean for city pairs with three intervening points to be reliably larger than that for pairs with two intervening points, and the mean for pairs with one intervening point to be reliably larger than that for pairs with no intervening points ($p < .05$).

A multiple-regression analysis was performed to test for the influence of other variables on subjects' distance estimates. The analysis was performed separately for the memory and perception tasks. For each analysis, the dependent variable was the mean distance estimate, across subjects, for the route between each of the 64 city pairs. Three variables in addition to true distance and clutter were entered into the regression equation. Two of these variables were measures of the familiarity of the judged route. Evidence from prior studies suggests that distance estimates are systematically influenced by subjects' familiarity with the endpoints and paths of the judged routes (Golledge, Briggs, & Demko, 1969; Stea, 1969). Therefore, for each city pair, the mean familiarity rating of the two cities was computed across subjects. This value served as one of the variables (Familiarity 1) in the regression. The second variable (Familiarity 2) was determined by computing the mean

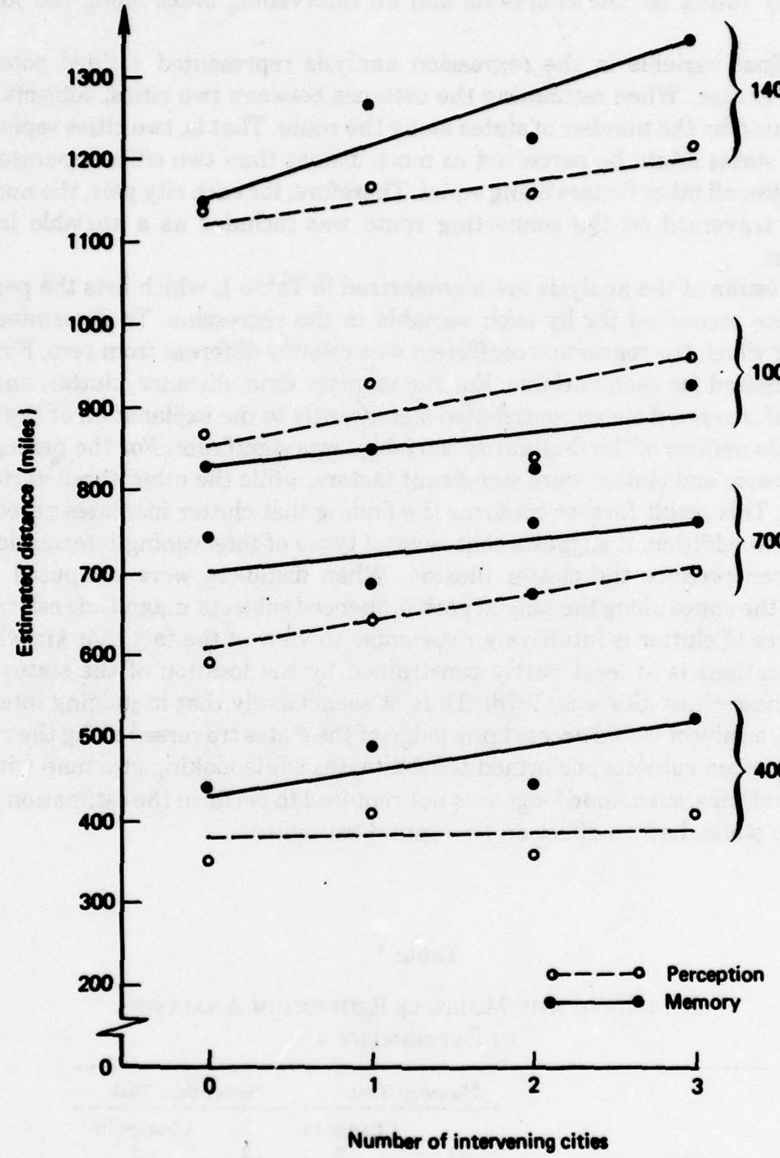

Fig. 6—Mean estimates of intercity distances in the United States in Experiment 4

familiarity rating for the endpoints and all intervening cities along the judged route.

The final variable in the regression analysis represented a third potential source of clutter. When estimating the distance between two cities, subjects may be influenced by the number of states along the route. That is, two cities separated by many states might be perceived as more distant than two cities separated by fewer states, all other factors being equal. Therefore, for each city pair, the number of states traversed on the connecting route was included as a variable in the regression.

The results of the analysis are summarized in Table 1, which lists the percent of variance accounted for by each variable in the regression. To determine the subset for which the regression coefficient was reliably different from zero, F ratios were computed for each variable. For the memory data, distance, clutter, and the number of traversed states contributed significantly to the explanation of the variance, while neither of the familiarity variables was significant. For the perception data, distance and clutter were significant factors, while the other three variables were not. This result further confirms the finding that clutter increases perceived distance. In addition, it suggests that several types of intervening information on a route can produce the clutter illusion. When distances were computed from memory, the states along the judged path influenced subjects' magnitude estimates. This source of clutter is intuitively reasonable in view of the fact that knowledge of city locations is at least partly constrained by the location of the states that contain those cities (Stevens, 1978). Thus, it seems likely that in judging intercity distances, a subject would access knowledge of the states traversed along the route. However, when subjects performed the estimates while looking at a map without state boundaries, such knowledge was not required to perform the estimation task; hence the states had no effect on perceptual estimates.

Table 1

RESULTS OF THE MULTIPLE-REGRESSION ANALYSIS IN EXPERIMENT 4

Variable	Memory Task R^2	Memory Task Change in R^2	Perception Task R^2	Perception Task Change in R^2
1. Distance	.742	.742[a]	.877	.877[a]
2. Traversed states	.771	.029[a]	.889	.012
3. Intervening cities	.797	.026[a]	.920	.031[a]
4. Familiarity 2	.815	.018	.921	.001
5. Familiarity 1	.816	.001	.921	.000

[a] $p < .05$.

III. DISCUSSION

The results from the four experiments of this study indicate that the presence of intervening points along a route increases subjects' estimates of the length of that route. This clutter illusion was present both in experiments using artificial materials and in those using materials with which subjects had substantial pre-experimental knowledge. Furthermore, the illusion occurred whether the estimation task was performed perceptually or from memory.

Shepard and his associates (e.g., Shepard & Podgorny, 1978; Shepard, 1978) have argued that similarities between results obtained on perceptual and memorial tasks indicate that subjects are using the same computations in both tasks. In the present experiments, subjects estimating distances from memory seem to be using a representation of the a map that, like the map itself, preserves the metric spatial relationships among cities. Such a memory representation may be activated as an image that can be scanned, just as an external map can be perceptually scanned. This conclusion has been supported by the findings in other studies that time to estimate distances in memory increases linearly with distance (Baum & Jonides, 1977; Hartley, 1977) and that time to scan across an image increases with distance and clutter (Kosslyn, 1978; Kosslyn et al., 1978).

The psychophysical data also indicate the similarity between perceptual and memorial processes. When clutter was held constant, both memorial and perceptual estimates of distance were power functions of their corresponding physical values. Thus, judgments of distance performed from memory demonstrated properties similar to those of judgments typically obtained with visual and other sensory stimuli. Furthermore, there was a close correspondence between the exponents of the best-fitting power functions for memorial and perceptual data. In both cases, the value of the best-fitting exponents indicated that subjects overestimated short distances and underestimated long distances.

The following discussion considers the process by which a subject actually arrives at an estimate of the distance between two cities. It is assumed that for both perceptual and memorial judgments, the subject scans a perceptual image of the route from the starting point to the destination, traversing the set of intervening cities along the way. By what mechanism is this visual scan converted into a judgment of magnitude?

A framework called an *analog timing model* is used here to explain subjects' performance on this task. Assume that when the subject scans along a route, the scan process activates an internal clock, or timer. At the end of the scan, the clock is stopped; the clock time indicates the elapsed scan time and, indirectly, the accumulated distance. The time can then be compared to the scan time for the standard modulus to convert the time estimate into a mileage estimate. That is, the scan time of the modulus and its stated mileage provide a conversion factor for translating the scan time for a test item into miles.

The results from several studies of time perception support the plausibility of the timing model for distance estimation. When subjects judge the duration of a time interval, their estimates are greater when stimuli occur between the bounding markers of the interval than when the interval is unfilled (Hall & Jastrow, 1886;

Grimm, 1934; Roeloefs & Zeeman, 1951; Buffardi, 1971; Thomas & Brown, 1974; Thomas & Weaver, 1975; Adams, 1977). The increase in such estimates is linear with the number of intervening stimuli (Buffardi, 1971) and is independent of the actual duration of the interval (Thomas & Brown, 1974). Finally, as Fig. 3 indicates, subjects similarly tend to overestimate short unfilled distances and underestimate long unfilled distances (Woodrow, 1934; Thomas & Brown, 1974). Eisler (1976), in a review of 100 years of subjective duration experiments, reported that the exponent for the psychophysical function for judged duration averaged approximately .9. This value corresponds closely to the exponents estimated for the data from Experiments 2 and 3 (see Fig. 5). Since the data from the distance-estimation tasks correspond so closely to the data from these time-estimation tasks, it is plausible that the same process underlies both judgments.

Six detailed models of how estimates are performed are considered below. The models embody different assumptions about the scanning process, but all assume the general timing model outlined above. Parameter estimates for the models were obtained and the models were comparatively evaluated by fitting them to the data from Experiments 2 and 3, using standard regression methods. The use of artificial materials in these experiments controlled for potential differences in degree of learning, familiarity, and extra-experimental knowledge. In contrast, the data from Experiment 4 were subject to all of these potentially spurious influences. In all cases, linear regression methods were used for parameter estimation. For nonlinear models, exponent values were estimated by convergence, using successive iteration on linear regression analyses.

Model 1: Linear Scanning Model. Model 1 is the simplest formulation of the timing model. It assumes that a subject estimating the length of a route initiates the internal timer, then scans along the route (passing through the intervening points) until the termination point is reached. At that point, the timer is deactivated and the cumulative time is converted into miles. The scan time along an empty line is assumed to be a linear function of the length of the route. However, when the scan is performed on a cluttered route, each intervening point requires the subject to stop the visual scan, retrieve the name of the city, and compare it with the name of the destination point. If the names do not match, the scan continues to the next city. This processing requires additional time, thus increasing the overall scan time and hence the resulting distance estimate. The scanning process and the operations required to test intervening points are assumed to be independent, so their contributions to the overall decision time are additive. The judged distance of a route (L'), then, can be expressed as the linear combination of the true distance (L) and the number of intervening points (C):

$$L' = b_0 + b_1 L + b_2 C \ . \qquad (2)$$

This model assumes a linear combination of distance and clutter in predicting distance estimates, with no interaction between the two variables. This assumption was supported by the analysis of variance for Experiments 2 and 3, which showed no significant interaction between these variables. Since the effect of intervening points is independent of the actual distance to be estimated, the proportional increase in estimates due to clutter decreases with increasing distance. That is, the longer the distance to be estimated, the smaller the relative effect of intervening points on the estimate. This seems intuitively reasonable, since, for example, when the line to be estimated is very long, the effect of a single intervening point would be expected to be negligible.

This scanning model was fit to the data from Experiments 2 and 3 independently. For both experiments, the fit of the model was significant: $F(2,18) = 51.56$, $p < .001$ for Experiment 2; $F(2,22) = 979.61$, $p < .001$ for Experiment 3. In addition, the contribution of the clutter variable to the explanation of the variance was significant, $F(1,18) = 4.57$, $p < .05$ for Experiment 2; $F(1,22) = 10.33$, $p < .01$ for Experiment 3. For both experiments, the linear scanning model accounted for a high percentage of the variance in the distance estimates, as shown in the first row of Table 2.

For Experiment 2, the parameter b_1 was estimated to be .97, and b_2 was estimated to be 15.36. For Experiment 3, the estimate of b_1 was identical to that for Experiment 2 (.97), while the estimate of b_2 was approximately half that for Experiment 2 (7.54). These estimates indicate that the relationship between physical distance and estimated distance is the same on both the memory and perception tasks but that intervening points on a route add twice as much to the distance estimate on the memory task as on the perception task. Considered in the timing framework, this result implies that intervening points produce longer pauses in the linear scan when the scan is performed in memory. A reasonable interpretation for this result is that the time required to retrieve the name of an intervening point is longer when the retrieval occurs in memory than when it is performed perceptually on the physical map. However, the rate of scanning along the route between points is the same in both conditions. The non-unitary estimate of $b_1 = .97$) indicates that the relationship between perceived length and true length is nearly, but not completely, veridical.

Each estimate of length requires, in addition to the line scan, the location of the line to be estimated (either on the map or on the mental image) and a comparison of the judged line to the standard modulus. These operations, while part of the overall estimation process, are presumably independent of the scan of the test line. Therefore, the constant b_0 should be zero. As the first row of Table 2 shows, b_0 was near zero for both Experiments 2 and 3. These parameter estimates did not differ reliably from zero ($F(1,18) = 0$ for Experiment 2, $F(1,22) = 0.53$ for Experiment 3).

This scanning model is consistent with results of other studies in which scan time or estimated time is the dependent variable. Hartley (1977) found that the time to estimate the length of a visually presented line increased linearly with line length. Kosslyn (1978) and Kosslyn et al. (1978) reported that the time to scan across a visual image was linear in the distance across the image. Furthermore, Lea (1975) and Kosslyn et al. argued that there was a time cost associated with processing each intervening point traversed along an imagined path between two terminal points. Further, both investigators found no interaction between distance and clutter in the time to scan across an image. That is, the time to process an intervening point was independent of the distance to be scanned across the image. Similarly, estimates of time duration are typically a linear function of true duration (Triesman, 1963; Craig, 1973; Thomas & Brown, 1974). Furthermore, the parameter estimate relating judged length to true length obtained here ($b_1 = .97$) corresponds closely to the estimates for the parameter relating judged duration to true duration ($b_1 = .98$ (Triesman, 1963); $b_1 = 1.0$ (Craig, 1973)).

Table 2

Alternative Models for the Distance Estimation Process

			Experiment 2		Experiment 3	
	Model	Equation	Percent of Variance Accounted For	Parameter Estimates	Percent of Variance Accounted For	Parameter Estimates
1.	Linear scanning	$b_0 + b_1 L + b_2 C$	85.3	$b_0 = -.95$, $b_1 = .97$, $b_2 = 15.36$	98.9	$b_0 = 4.72$, $b_1 = 97$, $b_2 = 7.54$
2.	Interaction	$b_0 + b_1 L + b_2 C + b_3 LC$	85.9	$b_0 = 30.93$, $b_1 = .80$, $b_2 = -3.00$, $b_3 = .09$	98.9	$b_0 = -5.11$, $b_1 = 1.00$, $b_2 = 13.56$, $b_3 = .02$
3.	Nonlinear scanning	$b_0 + b_1 L^n + b_2 C$	85.3	$b_0 = 13.25$, $b_1 = .52$, $b_2 = 15.42$, $n = 1.10$	98.9	$b_0 = 24.24$, $b_1 = .50$, $b_2 = 7.37$, $n = 1.10$
4.	Linear chunking (1)	$b_0 + (1+e)L$	81.3	$b_0 = 22.61$, $e = -.14$	96.4	$b_0 = 19.39$, $e = -.05$
5.	Linear chunking (2)	$b_0 + L + (C+1)e$	83.3	$b_0 = -24.75$, $e = 15.49$	98.5	$b_0 = -13.38$, $e = 7.83$
6.	Nonlinear chunking	$b_0 + \sum_{i=1}^{C+1} k l_i^n$	85.5	$b_0 = -4.11$, $k = 2.09$, $n = .84$	98.5	$b_0 = 8.12$, $k = 1.27$, $n = .95$
	when n = .95 for both experiments		83.4	$b_0 = 15.98$, $k = 1.27$, $n = .95$	. . .	. . . .
	when n = .84 for both experiments			. . . .	96.7	$b_0 = -13.14$, $k = 2.22$, $n = .84$

Model 2: Interaction Model. While the interaction between length and clutter was not significant in Experiments 2 and 3, the data from these experiments do not rule out the possibility of a small interaction. The best-fitting lines in Figs. 3 and 4 are visibly non-parallel, indicating the presence of a small interaction between the two variables. Model 2 incorporates an interaction term in the linear prediction equation for estimated distance, as follows:

$$L' = b_0 + b_1L + b_2C + b_3LC\ .$$

Since this model has one more parameter than the linear scanning model (Model 1), it should, in principle, fit the data better than Model 1. However, this is not the case in the second row of Table 2. Model 1 accounts for as much of the experimental variance as the interaction model in both Experiments 2 and 3. The best estimates of b_3 for the data from Experiments 2 and 3 were nearly zero (.09 and −.02, respectively). Accordingly, the incremental contribution of the interaction term (b_3) to prediction of the variance was not significant ($F < 1$ for both Experiments 2 and 3). Furthermore, for Experiment 2, the estimate of b_0 was much larger than the predicted value of zero, and that of b_2 (the clutter multiplier) was negative. Therefore, the linear scanning model appears to be preferable to the interaction model.

Model 3: Non-linear Scanning Model. The typical function relating true distance to estimated distance is a power function of the form given in Eq. (1). Suppose that the scanning model is an accurate description of the estimation process, but that the estimated scan time along the route, independent of clutter, is a power function of the actual distance or scan time. The scanning model given in Eq. (2) could thus be modified as follows:

$$L' = b_0 + b_1L^n + b_2C\ . \tag{3}$$

This model is a more general formulation of Model 1. (Equation (3) reduces to Model 1 when n = 1.) When this model was fit to the data from both Experiments 2 and 3, the best estimate of n was 1.10. However, as the third row of Table 2 indicates, allowing n to be a free parameter does not significantly improve the fit to the data. In addition, the estimates of b_0 differ greatly from the predicted value of zero ($F(1,22) = 7.78$, $p < .02$, for Experiment 3). Therefore, there is no reason to reject the more parsimonious linear model.

The next three models assume that the subject treats a cluttered route as a set of individual routes. When visually scanning a route or an image of a route, the subject encounters each city that intervenes between the starting point and the destination point. Models 4 through 6 assume that subjects estimate each segment defined by the intervening points separately. The overall estimate for the route is then the sum of the estimated subroutes. This class of models may be described by the equation

$$L' = b_0 + \sum_{i=1}^{C+1} l'_i\ ,$$

where l'_i is the estimated length of subroute i.

Model 4: Linear Chunking Model (1). Model 4 assumes that a subject estimates each subroute i with an error e that is proportional to the true magnitude of i (= l). Thus, an estimated route L′ may be expressed as

$$L' = b_0 + \sum_{i=1}^{C+1} l_i + el_i = b_0 + (1+e)L\,.$$

The fit of this model to the data is given in the fourth row of Table 2. It may be noted that this model is equivalent to Model 1 with $b_2 = 0$. The fit of this model to the data is nearly as good as that of Model 1. However, in Model 1, b_2 was not equal to zero and contributed significantly to the explanation of the experimental variance. That is, Model 1 provides a reliably better fit to the data than Model 4. Further, the estimated values of b_0 differed greatly from zero ($F(1,23) = 6.55$, $p < .05$ for Experiment 3). Therefore, Model 4 may be rejected as a competitor to the linear scanning model.

Model 5: Linear Chunking Model (2). Model 5 is similar to Model 4 in that it assumes that the estimate of each subroute has an associated error e. In this model, however, e is assumed to be independent of l_i. That is, the error in each estimate is constant for subroutes of all lengths. This relationship may be expressed as

$$L' = b_0 + \sum_{i=1}^{C+1} l_i + e = b_0 + L + (C+1)e\,.$$

This model is equivalent to Model 1, with the constraint that the parameter associated with L is equal to 1. This model provides a slightly worse fit to the data than Model 1, as shown in the fifth row of Table 2. In addition, under the constraint that the parameter associated with L must be 1 (compared to the estimate of .97 for Model 1), b_0 became substantially less than zero ($F(1,23) = 4.27$, $p < .05$ for Experiment 3). Thus, this model is also inferior to Model 1.

Model 6: Non-linear Chunking Model. Model 6 assumes that the estimate of each subroute l′ is a power function of the true distance l. Thus, this model may be expressed as

$$L' = b_0 + \sum_{i=1}^{C+1} kl_i^n\,. \tag{4}$$

Model 6, like the linear scanning model, has three parameters to be estimated. (Note, however, that when n is near or equal to 1, Model 6 is equivalent to Model 4.) As shown in Table 2, the two models provide comparable fits to the data. The estimated values for the exponent n in Model 6 were .84 for the memory experiment (Experiment 2) and .95 for the perception experiment (Experiment 3). These values are within the range normally obtained in magnitude-estimation experiments (Baird, 1970), but the values of b_0 are further from the predicted value of zero than the b_0's estimated for Model 1. However, it has been assumed that the visual scan along the line to be estimated is identical for both perception and memory tasks. This means that the parameter describing the relationship between distance and estimated distance should be identical (disregarding for the moment the effects of clutter). So, for example, the parameter estimate for the route distance factor in Model 1 (b_1) is the same for both memory and perception data (.97). If Model 6 is evaluated under the same constraint, then the exponent n in Eq. (4) should be the same as the data from Experiments 2 and 3. Accordingly, the fit of the model to the data was determined utilizing a single value for n. When n = .84 (the value providing the best fit in Experiment 2) was used, the model accounted for 96.7 percent of the variance (instead of 98.5 percent) in the Experiment 3 data. Similarly, when n = .95 (the estimate obtained from Experiment 3) was used, the model accounted for 83.4 percent of the variance in the Experiment 2 data. Thus, when n is constrained to be a single value, Model 6 fits the data slightly worse than Model 1.

This non-linear chunking model represents a special case of a class of chunking models postulated by Thomas and Brown (1974) to account for subjects' estimates of filled temporal intervals. Thomas and Brown also postulated that subjects estimate each time interval separately and sum the individual intervals to provide an overall estimate. They showed that whenever the subinterval estimate is a concave increasing function of the true value, the size of the produced illusion increases with n and is larger for regular than for irregular intervals. Model 6 is concave when $n < 1$, a condition satisfied by the parameter estimates obtained in fitting the model to the data.

SYMBOLIC ENCODING MODELS

All six of the distance-estimation models considered above assume that memory estimates are computed from a stored imaginal representation of the map and that the memory representation is a spatial analog of the physical map, preserving the topographic properties of the cities. An alternative framework for modeling this task assumes that subjects extract spatial information from the studied map and represent it in memory in an abstract, propositional form (Pylyshyn, 1973). For example, subjects might store in memory a network of nodes representing city names and links among the nodes that specify relative direction (north, east, west, south) and distance information. They then would perform distance estimates by retrieving the stored value or by sampling from some range of values associated with the path between two cities. Such "symbolic encoding" models presume that subjects estimate distances at the time they learn the map, and then merely retrieve those estimates when required to report them.

How might distances be estimated at encoding time under this framework? Despite the different structural assumptions about representation entailed by the imaginal and symbolic models, the process models for the initial estimation process itself are substantially the same. The subject presumably uses the scale distance given on the map as a standard against which to measure and then encode the route distances between cities. If the subject encodes route distances explicitly, then the three scanning models considered above (Models 1 through 3) would seem to be unlikely candidates for the estimation process. These models assume that the subject scans across intervening points to determine the distance between the starting point and the destination of a route. If subjects did not know at encoding time which routes would be tested, they would have to estimate the distances between all pairs of cities. For example, if cities A, B, C, and D lay along a road, subjects would have to estimate distances for A–B, A–C, A–D, B–C, B–D, and C–D. This procedure seems unlikely because of the effort required to perform all the estimates, and because subjects did not know they would ultimately be asked to estimate intercity distances.

A more reasonable alternative is that subjects encoded distances only between adjacent points (e.g., A–B, B–C, C–D) and then added the individual values when estimating a route that spanned intervening points (e.g., A–D). The chunking models (Models 4 through 6) embody these assumptions and could easily be formulated in the encoding framework. As discussed above, the linear chunking models (Models 4 and 5) do not fit the data as well as the linear image scanning model (Model 1). The non-linear chunking model (Model 6), however, provides an adequate account of the data. If, as the encoding model assumes, subjects store estimated distances during perception and merely retrieve them to perform memorial estimates, then the exponent estimated for the non-linear chunking model must be the same for the memorial (Experiment 2) and the perceptual (Experiment 3) tasks. As discussed previously, when this constraint is imposed on the chunking model, it is inferior to the scanning model.

Three other factors militate against acceptance of this encoding model. First, if memorial judgments reflect simple retrievals of values stored during perception, then judgments performed in the two conditions should be nearly identical. In particular, there is no reason to expect the effect of clutter on distance estimates to be attenuated in the perception task, as was observed here. Second, although subjects were free to use any strategy to compute distances, only one of fourteen subjects in Experiments 2 and 3 reported adding subroute distances to obtain overall distances between points. Finally, the symbolic encoding model does not adequately explain the relationship between reaction time and scan distance obtained in earlier studies (Kosslyn, 1978; Kosslyn et al., 1978). Thus, while the encoding model cannot be categorically rejected, it does not provide the best explanation for the present data.

COMPARATIVE EVALUATION OF ESTIMATION MODELS

As demonstrated by the preceding discussion and Table 2, the variances accounted for in fitting all the models to the data from Experiments 2 and 3 are roughly equivalent. However, when parsimony and the values of the estimated parameters are taken into account, the linear scanning model (Model 1) and the non-linear chunking model (Model 6) are the most appealing. On the basis of the data reported here, neither model can be unequivocally favored over the other; they account for nearly equal proportions of the variance in Experiments 2 and 3. Table 3 compares the fit of the two models to the data in more detail. This table shows the predicted values for the uncluttered routes in Experiments 2 and 3 as computed by the two models, using the best-fitting parameters. (The values of these parameters are given in Table 2.) The fit of Model 6 is given in Table 3 for the values of the exponent estimated from each experiment. Table 3 also gives the 95 percent confidence limits for each of the estimated distances. The predicted estimates of the two models vary from 1 percent (for the 100-mile route in Experiment 2) to 20 percent (for the 400-mile route in Experiment 3). For several of the distances, the 95 percent confidence intervals for the models' predictions do not overlap, while in other cases the differences in predicted values are negligible. Thus, while the relative fit of the models to the data is quite close, the models differ in many of their predictions for individual test items.

Several other factors should also be considered in comparatively evaluating these two models. Model 1 is intuitively appealing because it is consistent with earlier magnitude-estimation results. The exponent of the power function relating

Table 3

DISTANCE ESTIMATES FOR UNCLUTTERED ROUTES IN EXPERIMENTS 2 AND 3 PREDICTED BY MODELS 1 AND 6 USING ESTIMATED PARAMETERS

		Model 1 *Linear Scanning*		Model 6 Non-Linear Chunking (n = .84)		Model 6 Non-Linear Chunking (n = .95)	
True Distances, L (miles)	Mean of Subjects' Estimates, L'	$\hat{L}'$	95 percent limits	$\hat{L}'$	95 percent limits	$\hat{L}'$	95 percent limits
Experiment 2							
100	105.33	96.05	±20.41	95.92	±21.81	116.86	±24.41
200	181.00	193.05	±12.30	174.96	±13.72[a]	210.87	±15.75[a]
300	275.00	290.05	±20.41[a]	247.62	±21.81[a,b]	302.44	±24.41[b]
Experiment 3							
100	94.00	102.63	± 8.81	93.12	±14.75	109.00	±10.09
200	199.00	199.63	± 5.53[a]	177.06	± 9.26[a]	203.00	± 6.34
300	302.00	296.63	± 5.53[a]	254.24	± 9.26[a]	294.58	± 6.34
400	404.00	393.63	± 8.81[a]	327.33	±14.75[a]	384.62	±10.09

Note: Within each row, numbers with the same superscript (a or b) indicate non-overlapping estimates.

distance to estimated distance, as predicted by Model 1, is typically 1 or very close to 1 (Baird, 1970; Stevens, 1975). Further, when subjects scan across a mental image or visual display, the reaction time is linear with the distance (Baum & Jonides, 1977; Hartley, 1977; Kosslyn, 1978; Kosslyn et al., 1978). The best fit to the data that can be obtained with Model 6, in contrast, uses exponent values of .84 and .95. In his review of magnitude-estimation studies of length, Baird (1970) found only 2 of the 29 exponents estimated for the power function to deviate from 1.0 by as much as .84 does (±.16).

Indirect evidence supporting the scanning model was also obtained from subjects' reports of their strategies for estimating route distances. All six subjects in Experiment 2 and seven of the eight subjects in Experiment 3 reported using the 75-mile standard as a reference. That is, they tried to scan across the line to be estimated and determine its length by multiplying 75 by the number of times the standard would fit along the test line. All subjects reported being aware of the intervening cities during this process, even though the cities were not used in making the measurement. Only one subject, from Experiment 3, reported using the intervening cities in the estimation process. This subject attempted to compute the distance between each pair of adjacent cities on the route, and then added these distances to get the overall route distance. This is the process suggested by the non-linear chunking model (Model 6).

On the other hand, Model 6 has the advantage that it predicts different effects of n intervening cities, depending upon the distribution of the cities along the route.

In particular, it predicts that the increase in the estimated distance should be larger when the cities are distributed regularly along the route than when they are distributed irregularly (Thomas & Brown, 1974). In contrast, the linear scanning model predicts no difference between regular and irregular distributions. While the superiority of the illusion for regular distributions has been obtained for interval-duration estimates (Grimm, 1934), its reliability is equivocal (cf. Thomas & Brown, 1974). In the present experiments, the distribution of intervening points along the routes was not varied systematically. However, it is possible to compare subjects' mean estimates for a given distance and value of clutter in those cases where the items comprised both equally and unequally segmented routes. In Experiment 2, eight of the possible nine conditions (clutter = 1, 2, or 3; distance = 100, 200, or 300 miles) contained items of both types. In only two of the eight cases were the mean estimated distances for equally segmented routes greater than those for unequally segmented routes. In Experiment 3, a similar comparison was possible for six of the experimental conditions. Here, mean estimates of equally segmented routes exceeded those of unequally divided routes in only three of the six comparisons. Therefore, the superiority of the illusion for regular distributions was not confirmed in the present experiments. Nevertheless, it seems likely that the clutter effect could be attenuated with extremely irregular distributions. For example, if three intervening cities were placed almost on top of one another extremely close to one of the terminal points on a route, the route would perceptually approximate an uncluttered route, and the resulting distance estimate might not show the effect of clutter. In the present experiments, occurrences of irregular clutter were not this extreme, and the effects of these extreme cases remains to be determined empirically. Such a determination would seem to be required for a comprehensive elaboration of a cognitive theory of distance estimation.

While all subjects in these experiments seemed to be estimating distances from memory, using an image of the map, this technique is undoubtedly but one of several strategies that people use. Clearly, in real-world situations, people have the ability to compute or infer distances symbolically, based on a variety of types of stored knowledge. When a person learns a map of an unfamiliar area, the ability to reconstruct an image of that map may deteriorate over long retention intervals. In such situations, many other factors may influence the estimation process. However, the present studies indicate a systematic bias that occurs reliably when people estimate distances by scanning either memorized or physical maps of both familiar and unfamiliar regions.

These results may have important policy implications for the future design of maps, particularly computer-generated graphic displays (e.g., Anderson & Shapiro, 1979). Many maps are difficult to use because they are overcrowded with data. In fact, Taylor and Hopkin (1975) point to map clutter as the greatest single problem in map design. It is widely held that clutter introduces noise that interferes with reading and using maps, the present study suggests that clutter also introduces a systematic bias in particular judgments made using a map. Consequently, in designing dynamic, computer-generated maps of the future, researchers should consider the desirability of presenting geographic displays that supply requested information but minimize the amount of attendant, irrelevant data. Such request-driven displays could provide the data needed for particular purposes without introducing biases that result from the use of cluttered images.

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Navy

1 Dr. Robert Blanchard
Navy Personnel R&D Center
Management Support Department
San Diego, CA 92151

1 Dr. Jack R. Borsting
Provost & Academic Dean
U.S. Naval Postgraduate School
Monterey, CA 93940

1 Dr. Robert Breaux
Code N-71
NAVTRAEQUIPCEN
Orlando, FL 32813

1 Dr. Pat Federico
Navy Personnel R&D Center
San Diego, CA 92152

1 Lt. Steven D. Harris, MSC, USN
Code 6021
Naval Air Development Center
Warminster, PA 18974

1 Dr. Norman J. Kerr
Chief of Naval Technical Training
Naval Air Station Memphis (75)
Millington, TN 38054

1 Dr. William L. Maloy
Principal Civilian Advisor for
Education and Training
Naval Training Command, Code 00A
Pensacola, FL 32508

1 Dr. Kneale Marshall
Scientific Advisor to DCNO(MPT)
OP01T
Washington, D. C. 20370

1 Capt. Richard L. Martin
USS Francis Marion (LPA-Z49)
FPO New York, NY 09501

2 Dr. James McGrath
Navy Personnel R&D Center
Code 306
San Diego, CA 92152

1 Cdr. Mercer
CNET Liaison Officer
AF Human Resources Lab./Flying
Training Division
Williams AFB, AZ 85224

Navy

1 Dr. George Moeller
Head, Human Factors Branch
Naval Submarine Medical Research Lab.
Groton, CN 06340

1 Dr. William Montague
Navy Personnel R&D Center
San Diego, CA 92152

1 Naval Medical R&D Command
Code 44
National Naval Medical Center
Bethesda, MD 20014

1 Library
Navy Personnel R&D Center
San Deigo, CA 92152

6 Commanding Officer
Naval Research Laboratory
Code 2627
Washington, D. C. 20390

1 John Olsen
Chief of Naval Education & Training
Support
Pensacola, FL 32509

1 Psychologist
ONR Branch Office
495 Summer Street
Boston, MA 02210

1 Psychologist
ONR Branch Office
536 S. Clark Street
Chicago, IL 60605

1 Office of Naval Research
Code 437
800 N. Quincy Street
Arlington, VA 22217

5 Personnel & Training Research
Programs (Code 458)
Office of Naval Research
Arlington, VA 22217

1 Psychologist
Office of Naval Research Branch
223 Old Marylebone Road
London, NW
15th ENGLAND

Navy

1 Psychologist
ONR Branch Office
1030 East Green Street
Pasadena, CA 91101

1 Scientific Director
Office of Naval Research
Scientific Liaison Group/Tokyo
American Embassy
APO San Francisco, CA 96503

1 Office of the Chief of Naval Operations
Research, Development, and Studies Branch (OP-102)
Washington, D.C. 20350

1 Lt. Franck C. Petho, MSC, USNR (Ph.D)
Code L51
Naval Aerospace Medical Research Laboratory
Pensacola, FL 32508

1 Dr. Richard A. Pollak
Academic Computing Center
U.S. Naval Academy
Annapolis, MD 21402

1 Dr. Gary Poock
Operations Research Department
Naval Postgraduate School
Monterey, CA 93940

1 Roger W. Remington, Ph.D
Code L52
Naval Aerospace Medical Research Laboratory
Pensacola, FL 32508

1 Mr. Arnold Rubenstein
Naval Personnel Support Technology
Naval Material Command (08T244)
Room 1044, Crystal Plaza #5
2221 Jefferson Davis Highway
Arlington, VA 20360

1 Dr. Worth Scanland
Chief of Naval Education and Training
Code N-5
NAS, Pensacola, FL 32508

1 A. A. Sjoholm
Technical Support, Code 201
Navy Personnel R&D Center
San Diego, CA 92152

Navy

1 Mr. Robert Smith
Office of Chief of Naval Operations
OP-987E
Washington, DC 20350

1 Dr. Alfred F. Smode
Training Analysis & Evaluation Group (TAEG)
Department of the Navy
Orlando, FL 32813

Army

1 Dr. Richard Sorensen
Navy Personnel R&D Center
San Diego, CA 92152

1 HQ USAREUE & 7th Army
Office, DCS/Operations
USAAREUE Director of GED
APO New York 09403

1 Lt. Col. Gary Bloedorn
Training Effectiveness Analysis Division
US Army TRADOC Systems Analysis Activity
White Sands Missile Range, NM 88002

1 Dr. Ralph Dusek
US Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Commander
USAETL
Attention: ETL-GS-P
Fort Belvoir, VA 22060

1 Dr. Beatrice J. Farr
Army Research Institute (PERI-OK)
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Col. Frank Hart
Army Research Institute for the Behavioral & Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Ed Johnson
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Michael Kaplan
US Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Army

1 Dr. Milton S. Katz
Individual Training & Skill Evaluation Technical Area
US Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Technical Director
US Army Human Engineering Labs.
Aberdeen Proving Ground, MD 21005

1 Dr. Harold F. O'Neil, Jr.
Attn: PERI-OK
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Robert Sasmor
US Army Research Institute for the Behavioral and Social Scien
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Joseph Ward
US Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Air Force

1 Air University Library
AUL/LSE 76/443
Maxwell AFB, AL 36112

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HQ. AFHRL (AFSC)
AF Human Resources Lab.
Brooks AFB, TX 78235

1 Dr. G. A. Eckstrand (AS)
AF Human Resources Lab.
Wright-Patterson AFB, OH 45433

1 Dr. Genevieve Haddad
Program Manager
Life Sciences Directorate
AF Office of Scientific Research
Bolling AFB, DC 20332

1 Dr. Marty Rockway (AFHRL/TT)
AF Human Resources Lab.
Lowry AFB, CO 80230

2 Faculty Development Division
Headquarters Sheppard Technical
Training Center (ATC)
Sheppard AFB, TX 76311

1 Maj. Jack A. Thorpe
USAF
Naval War College
Providence, RI 02846

1 Lt. Col. Brian K. Waters
USAF
Air University
Maxwell AFB
Montgomery, AL 36112

Marines

1 H. William Greenup
Education Advisor (E031)
Education Center, MCDEC
Quantico, VA 22134

1 Special Assistant for Marine
Corps Matters
Code 100M
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

1 Dr. A. L. Slafkosky
Scientific Advisor (Code RD-1
Hq. U.S. Marine Corps.
Washington, D. C. 20380

Coast Guard

1 Maj. Jack Wallace
Headquarters, Marine Corps.
OTTI 31
Arlington Annex
Columbia Pike at Arlington Ridge Rd.
Arlington, VA 20380

Other DoD

1 Mr. Richard Lanterman
Psychological Research (G-P-1/62)
U.S. Coast Guard HQ.
Washington, D. C. 20590

12 Defense Technical Information Cen
Cameron Station, Bldg. 5
Alexandria, VA 22314
Attn: TC

1 Dr. Craig I. Fields
Defense Advanced Research Project
Agency
1400 Wilson Boulevard
Arlington, VA 22209

1 Dr. Dexter Fletcher
Defense Advanced Research Project
Agency
1400 Wilson Boulevard
Arlington, VA 22209

1 Mr. Armando Mancini
Headquarters, Defense Mapping
Agency
Building 56
Naval Observatory
Massachusetts Avenue at 34th St.,N
Washington, D. C. 20390

Other Gov't

1 Military Assistant for Training and Personnel Technology
Office of the Under Secretary of Defense for Research & Engineering
Room 3D129, The Pentagon
Washington, D. C. 20301

1 Dr. Susan Chipman
Basic Skills Program
National Institute for Education
1200 19th Street, N. W.
Washington, D. C. 20208

1 Dr. Joseph L. Lipson
Division of Science Education
Room W-638
National Science Foundation
Washington, D. C. 20550

1 Dr. John Mays
National Institute of Education
1200 19th Street, N. W.
Washington, D. C. 20208

1 Dr. Arthur Melmen
National Institute of Education
1200 19th Street, N. W.
Washington, D. C. 20208

1 Dr. Andrew R. Molnar
Science Education Development and Research
National Science Foundation
Washington, D. C. 20550

1 Dr. Joseph L. Young
Memory & Cognitive Processes
National Science Foundation
Washington, D. C. 20550

Non Gov't

1 Dr. John R. Anderson
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

1 Dr. John Annett
Department of Psychology
University of Warwick
Coventry CV4 7AL
ENGLAND

1 Dr. Michael Atwood
Science Applications Institute
40 Denver Technical Center West
7935 E. Prentice Avenue
Englewood, CO 80110

1 1 Psychological Research Unit
Department of Defense (Army Offic
Campbell Park Offices
Canberra ACT 2600
AUSTRALIA

1 Dr. Alan Baddeley
Medical Research Council
Applied Psychology Unit
Department of Psychology
Brown University
Providence, RI 02912

1 Dr. Patricia Baggett
Department of Psychology
University of Denver
University Park
Denver, CO 80208

1 Mr. Avron Barr
Department of Computer Science
Stanford University
Stanford, CA 94305

1 Dr. Nicholas A. Bond
Department of Psychology
Sacramento State College
600 Jay Street
Sacramento, CA 95819

1 Dr. Lyle Bourne
Department of Psychology
University of Colorado
Boulder, CO 80302

Non Gov't

1 Dr. Kenneth Bowles
Institute for Information Sciences
University of California at San Diego
La Jolla, CA 92037

1 Dr. John S. Brown
XEROX Palo Alto Research Center
3333 Coyote Road
Palo Alto, CA 94304

1 Dr. Bruce Buchanan
Department of Computer Science
Stanford University
Stanford, CA 94305

1 Dr. C. Victor Bunderson
WICAT Inc.
University Plaza, Suite 10
1160 So. State Street
Orem, UT 84057

1 Charles Myers Library
Livingstone House
Livingstone Road
Stratford
London E15 2LJ
ENGLAND

1 Dr. William Chase
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

1 Dr. Micheline Chi
Learning R&D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

1 Dr. William Clancey
Department of Computer Science
Stanford University
Stanford, CA 94305

1 Dr. Allan M. Collins
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02138

Non Gov't

1 Dr. Meredith P. Crawford
American Psychological Association
1200 17th Street, N. W.
Washington, D. C.

1 Mr. Ken Cross
Anacapa Sciences, Inc.
P.O. Drawer Q
Santa Barbara, CA 93102

1 Dr. Hubert Dreyfus
Department of Philosophy
University of California
Berkeley, CA 94720

1 Maj. I. N. Evonic
Canadian Forces Personnel Applied
1107 Avenue Road
Toronto, Ontario
CANADA

1 Dr. Ed Feigenbaum
Department of Computer Science
Stanford University
Stanford, CA 94305

1 Mr. Wallace Feurzeig
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02138

1 Dr. Victor Fields
Department of Psychology
Montgomery College
Rockville, MD 20850

1 Dr. Edwin A. Fleishman
Advanced Research Resources Office
Suite 900
4330 East West Highway
Washington, D. C. 20014

1 Dr. John D. Folley, Jr.
Applied Sciences Associates Inst.
Valencia, PA 16059

1 Dr. John R. Frederiksen
Bolt, Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02138

Non Gov't

1 Dr. Alinda Friedman
Department of Psychology
University of Alberta
Edmonton, Alberta
CANADA T6G 2J9

1 Dr. R. Edward Geiselman
Department of Psychology
University of California
Los Angeles, CA 90024

1 Dr. Robert Glaser
Learning R&D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

1 Dr. Marvin Glock
Department of Education
Stone Hall
Cornell University
Ithaca, NY 14853

1 Dr. Ira Goldstein
XEROX Palo Alto Research Center
3333 Coyote Road
Palo Alto, CA 94304

1 Dr. James G. Greeno
Learning R&D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

1 Dr. Barbara Hayes-Roth
The Rand Corporation
1700 Main Street
Santa Monica, CA 90406

1 Dr. Frederick Hayes-Roth
The Rand Corporation
1700 Main Street
Santa Monica, CA 90406

1 Dr. Adrian Hill
Vision and Ergonomics Research
Glascow College of Technology
Cowcaddens Road
Glascow G4 OBA
SCOTLAND

Non Gov't

1 Library
HumRRO/Western Division
27857 Berwick Drive
Carmel, CA 93921

1 Dr. Earl Hunt
Department of Psychology
University of Washington
Seattle, WA 98105

1 Dr. Kay Inaba
21116 Vanowen Street
Canoga Park, CA 91303

1 Dr. Lawrence B. Johnson
Lawrence Johnson & Assoc., Inc.
Suite 502
2001 "S" Street, N. W.
Washington, D. C. 20009

1 Dr. Arnold F. Kanarick
Honeywell, Inc.
2600 Ridgeway Parkway
Minneapolis, MN 55413

1 Dr. Walter Kintsch
Department of Psychology
University of Colorado
Boulder, CO 80302

1 Dr. David Kieras
Department of Psychology
University of Arizona
Tucson, AZ 85721

1 Dr. Kenneth Klivington
Alfred P. Sloan Foundation
630 Fifth Avenue
New York, NY 10020

1 Dr. Stephen Kosslyn
Harvard University
Department of Psychology
33 Kirkland Street
Cambridge, MA 02138

1 Mr. Marlin Kroger
1117 Via Golete
Palos Verdes Estates, CA 90274

Non Gov't

1 Lt. Col. C.R.J. Lafleur
Personnel Applied Research
National Defense Hqs.
101 Colonel By Drive
Ottawa
CANADA K1A OK2

1 Dr. Jill Larkin
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

1 Dr. Alan Lesgold
Learning R&D Center
University of Pittsburgh
Pittsburgh, PA 15260

1 Dr. Robert A. Levit
Manager, Behavioral Sciences
The BDM Corporation
7915 Jones Branch Drive
McClean, VA 22101

1 Dr. Robert R. Mackie
Human Factors Research, Inc.
6780 Cortona Drive
Santa Barbara Research Pk.
Goleta, CA 93017

1 Dr. Mark Miller
Systems and Information Sciences
Central Research Laboratories
Texas Instruments, Inc.
Mail Station 5
Post Office Box 5936
Dallas, TX 75222

1 Dr. Richard B. Millward
Department of Psychology
Hunter Laboratories
Brown University
Providence, RI 82912

1 Dr. Allen Munro
University of Southern California
Behavioral Technology Laboratories
3717 South Hope Street
Los Angeles, CA 90007

Non Gov't

1 Dr. Donald A. Norman
Department of Psychology C-009
University of California,
San Diego
La Jolla, CA 92093

1 Dr. Robert Pachella
Department of Psychology
Human Performance Center
330 Packard Road
Ann Arbor, MI 48104

1 Dr. Seymour Pachella
Department of Psychology
Human Performance Center
330 Packard Road
Ann Arbor, MI 48104

1 Mr. Luigi Petrullo
2431 N. Edgewood Street
Arlington, VA 22207

1 Dr. Peter Polson
Department of Psychology
University of Colorado
Boulder, CO 80302

1 Dr. Peter B. Read
Social Science Research Council
605 Third Avenue
New York, New York 10016

1 Dr. Fred Reif
SESAME
c/o Physics Department
University of California
Berkeley, CA 94720

1 Dr. Andrew M. Rose
American Institutes for Research
1055 Thomas Jefferson Street, N. W.
Washington, D. C. 20007

1 Dr. Ernst Z. Rothkopf
Bell Laboratories
600 Mountain Avenue
Murray Hill, NJ 07974

Non Gov't

1 Dr. David Rumelhart
Center for Human Information
University of California, San Diego
La Jolla, CA 92093

1 Dr. Walter Schneider
Department of Psychology
University of Illinois
Champaign, IL 61820

1 Dr. Allen Schoenfeld
Department of Mathematics
Hamilton College
Clinton, NY 13323

1 Dr. Robert J. Seidel
Instructional Technology Group
HumRRO
300 N. Washington Street
Alexandria, VA 22314

1 Dr. Robert Smith
Department of Computer Science
Rutgers University
New Brunswick, NJ 08903

1 Dr. Richard Snow
School of Education
Stanford University
Stanford, CA 94305

1 Dr. Kathryn T. Spoehr
Department of Psychology
Brown University
Providence, RI 02912

1 Dr. Robert Sternberg
Department of Psychology
Yale University
Box 11A, Yale Station
New Haven, CT 06520

1 Dr. Albert Stevens
Bolt, Beranek, & Newman, Inc.
50 Moulton Street
Cambridge, MA 02138

Non Gov't

1 Dr. Thomas Sticht
HumRRO
300 N. Washington Street
Alexandria, VA 22314

1 Dr. David Stone
ED 236
SUNY, Albany
Albany, NY 12222

1 Dr. Patrick Suppes
Institute for Mathematical Studies
and the Social Sciences
Stanford University
Stanford, CA 94305

1 Dr. John Thomas
IBM Thomas J. Watson Research Inst.
P.O. Box 218
Yorktown Heights, NY 10598

1 Dr. Douglas Towne
Behavioral Technology Labs.
University of Southern California
3717 South Hope Street
Los Angeles, CA 90007

1 Dr. J. Uhlaner
Perceptronics, Inc.
6271 Variel Avenue
Woodland Hills, CA 91364

1 Dr. Benton J. Underwood
Department of Psychology
Northwestern University
Evanston, IL 60201

1 Dr. William B. Whitten, II
Department of Psychology
SUNY, Albany
1400 Washington Avenue
Albany, NY 12222

1 Dr. Christopher Wickens
Department of Psychology
University of Illinois
Champaign, IL 61820

Non Gov't

1 Dr. Karl Zinn
Center for Research on Learning
and Teaching
University of Michigan
Ann Arbor, MI 48104

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